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Carbon Dioxide Uptake by a Temperate Tidal Sea

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***Abstract*—Carbon dioxide (CO_2) exchange between the atmosphere and the Wadden Sea, a shallow coastal region along the northern Netherlands, has been measured from April 2006 onwards on a tidal flat and over open water. Tidal flat measurements were done using a flux chamber, and ship borne measurements using an equilibrator to determine the partial pressure of CO_2 in the water. A strong response of CO_2 exchange rate on irradiance changes was observed at the tidal flat surface, with generally strong uptake of CO_2 during daylight conditions and release, presumably due to respiration, during dark conditions. The rate of respiration appeared to increase with temperature. Daytime CO_2 uptake tended to be higher than nighttime release all year round. Apparently, tidal flats in temperate regions of the globe may be a sink for CO_2 on an annual basis. In contrast to terrestrial CO_2 exchange, uptake by processes active on and in tidal flats responds only slowly to changing irradiance. This slow reaction is attributed to CO_2 storage in wet soil. Measurements in the water between tidal flats suggest that the estuarine, open water part of the Wadden Sea is a source of CO_2 in spring.**

***Index Terms*—Carbon dioxide, Flux chamber, Tidal flat.**

I. Introduction

Global warming is almost certainly influenced by fossil fuel burning and related human activities[1]. In order to improve estimates of the consequences of anthropogenically released CO_2, the biogeochemical cycle of CO_2 is widely studied nowadays. An important part of the CO_2 cycle is exchange with the oceans. A major uncertainty in the CO_2 budget is caused by exchange in coastal seas. Over 40% of carbon sequestration in the oceans occurs along continental margins [2]. Large variations in CO_2 fluxes at continental margins are, however, common. Close to the Netherlands, the North Sea has been found to be a sink for CO_2 [3], whereas the estuaries of Elbe, Ems, Rhine and Scheldt appeared to act as sources of CO_2 [4]. The direction of CO_2 exchange in the Wadden Sea, a tidal flat area to the north of the Netherlands and Germany and to the west of Denmark, has so-far not been established. Atmospheric fluxes of CO_2 have since a few years been measured regularly at a height of 50 m at Lutjewad at the edge of the Wadden Sea north of the city of Groningen. These measurements should inform on average surface exchange in a 10 km upwind direction. The surface of the Wadden Sea is highly variable over such distances, with alternating open water and tidal flats, depending on tide. The aim of the present study is to determine CO_2 fluxes from the main surface elements of the Wadden Sea: tidal flats and open water. These fluxes are needed to analyse atmospheric fluxes, observed from the Lutjewad tower. Moreover, the fluxes may inform on biological productivity as a basis of the food web on tidal flats and in open water of the Wadden Sea, an area of great ecological significance.

II. Method and Instrumentation

A. Tidal flat

Exchange of CO_2 between the atmosphere and the tidal flat was measured using the flux chamber method [6] once every month starting in April 2006. The chamber is transparent for sunlight, see figure 1. Within the flux chamber, the change of carbon dioxide concentration with time is measured using a Vaisala GMP343 open path analyser. A small ventilator is used to get a uniform CO_2 concentration in the chamber. Respiration during dark conditions is measured by placing a gas transmittent grey cloth on the flat and waiting until the

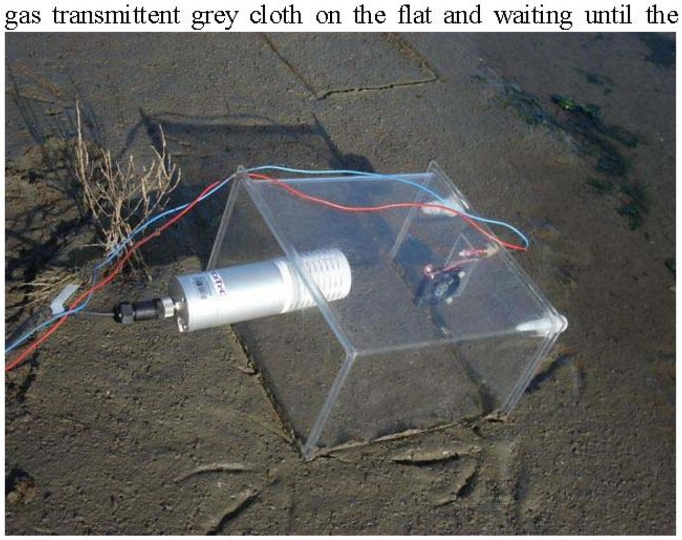

Fig. 1. The flux chamber placed on a tidal flat. Left in the chamber is the Vaisala CO_2 probe, right the ventilator, fed by a small accumulator. Dimensions of the flux chamber are 0.25 x 0.25 x 0.15 m.

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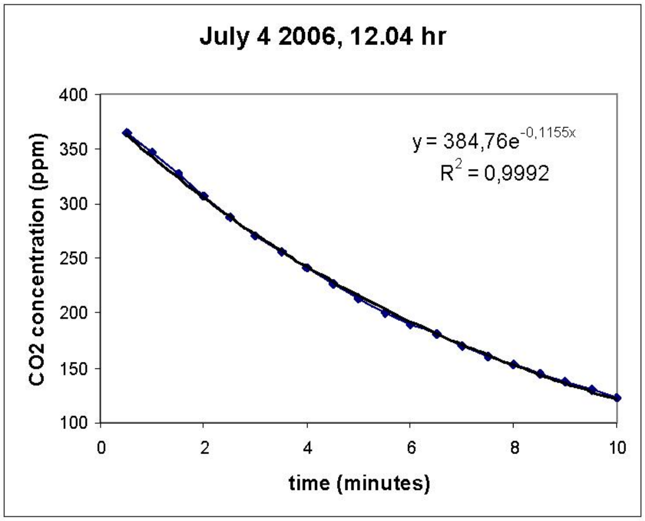

Fig. 2. Carbon dioxide concentration versus time during an observation on July 4, 2006 when temperature (34 ^{0}C) and solar irradiance (830 W m^{-2}) were high.

system is acclimatized to dark conditions.

A single flux chamber measurement takes 10 minutes. This time interval is sufficiently long to determine the temporal gradient of CO_2 in the chamber and short enough to keep temperature changes in the chamber small. Temperature changes in the chamber were generally within 1 ^{0}C during the measurements and the influence of incomplete transparency of the housing on CO_2 exchange is restricted as discussed later on. However, the exchange rate is influenced by changes in CO_2 concentration during the 10 minutes interval. During extreme situations uptake of CO_2 by the tidal flat shows an exponential decrease with time, see fig. 2. The exponential decrease can be understood as uptake rate depends on available concentration. Thus, all data where CO_2 concentration decreases with time were fitted exponentially. The flux was calculated from the exponential fitted temporal gradient at the onset of the measurement. Measurements where CO_2 concentration increases with time were fitted linearly.

B. *Open water*

Ship borne measurements were taken from the Asterias ship, owned by Rijkswaterstaat, using an equilibrator after a design by [4]. Water from a depth of 1 m is pumped at a high rate towards the equilibrator. In the equilibrator, a closed circuit of air is in intense contact with the water, and CO_2 concentration of the air is measured using a LICOR LI-6262 H_2O/CO_2 closed path analyser.

III. SITE DESCRIPTION

Fig. 3 shows a map of the Wadden Sea. The measurements on tidal flat were executed on the edge of the Wadden Sea halfway between the city of Groningen and the island Schiermonnikoog. Most of the flat consists of a muddy surface

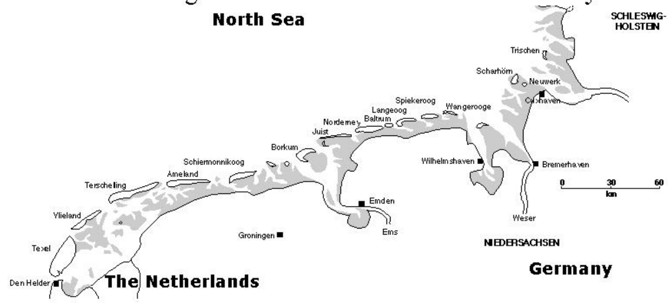

Fig. 3. Map of Wadden Sea. Source: W.W.F. Grey areas commonly fall dry during low tide

of a few centimeters depth on top of a sandy underground. The surface is brownish due to the presence of diatoms. At 1-2 cm depth an anoxic black layer is common with sulphur cycling bacteria. The flat is flooded during high tide only. The tidal flat is not completely flat. At higher locations within the flat the surface is mainly sandy and depressions are filled with salt water during the complete tidal cycle. Measurements were generally taken at 4 locations around the boundary between the sandy and the muddy parts of the flat. Occasionally, some measurements were taken on a thin layer of water in a depression.

Ship borne measurements were taken in the Dollard estuary between the city of Emden and the island Borkum.

IV. RESULTS

A. *Tidal flat dark measurements*

Figure 4 shows measurements of CO_2 concentration versus time. Measurements started about 15 minutes after the site was made dark, so uptake of CO_2 is measured up to 50 minutes of exposure to darkness. The apparent slow acclimatization of CO_2 flux to changing light conditions has two implications for data analysis of this study:

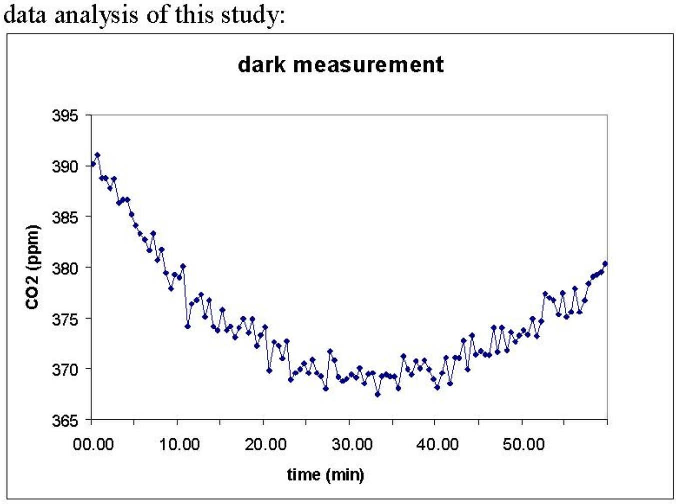

Fig. 4. Carbon dioxide concentration in the measurement chamber versus time. The measurements were executed during

daytime and started around 15 minutes after the soil was screened from light.

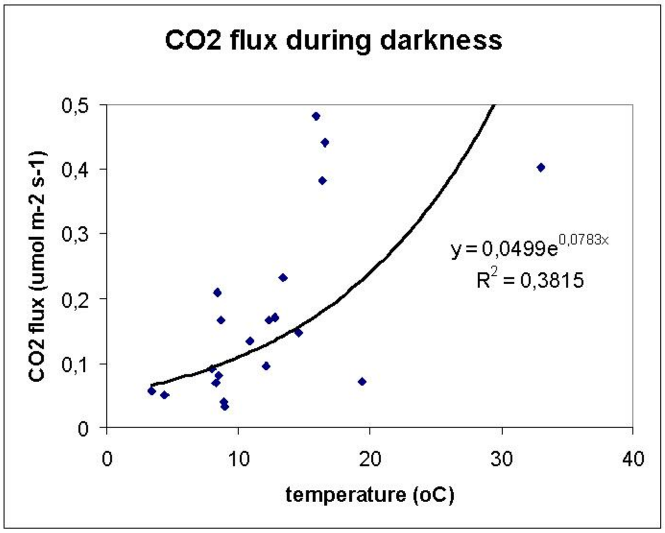

Fig. 5. All CO_2 fluxes during dark conditions versus temperature between April 2006 and March 2007 and fitted exponentially.

1) The site had to be covered at least one hour before a dark measurement could be used in the analysis
2) All CO_2 fluxes were related to mean irradiance in the hour PRECEDING the flux measurement.

All dark measurements of the first year of observation have been combined and are shown in figure 5 versus temperature inside the CO_2 analyzer. As a rule of thump, temperature within the analyser exceeds upper soil temperature by 2 ^{0}C.

B. *Tidal flat daylight measurements*

All measurements during a day are plotted versus solar irradiance. Figure 6 gives an example of all measurements during two consecutive days (April 12-13, 2006), where observations during the first day were made in the afternoon until dark and the following day from sunrise until the middle

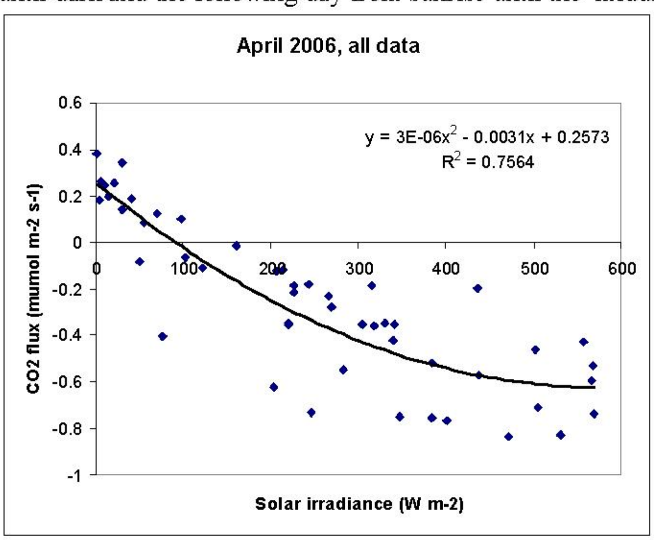

Fig. 6. CO_2 flux versus irradiance on April 12-13, 2006. Positive values indicate upward CO_2 fluxes, or release from the tidal flat.

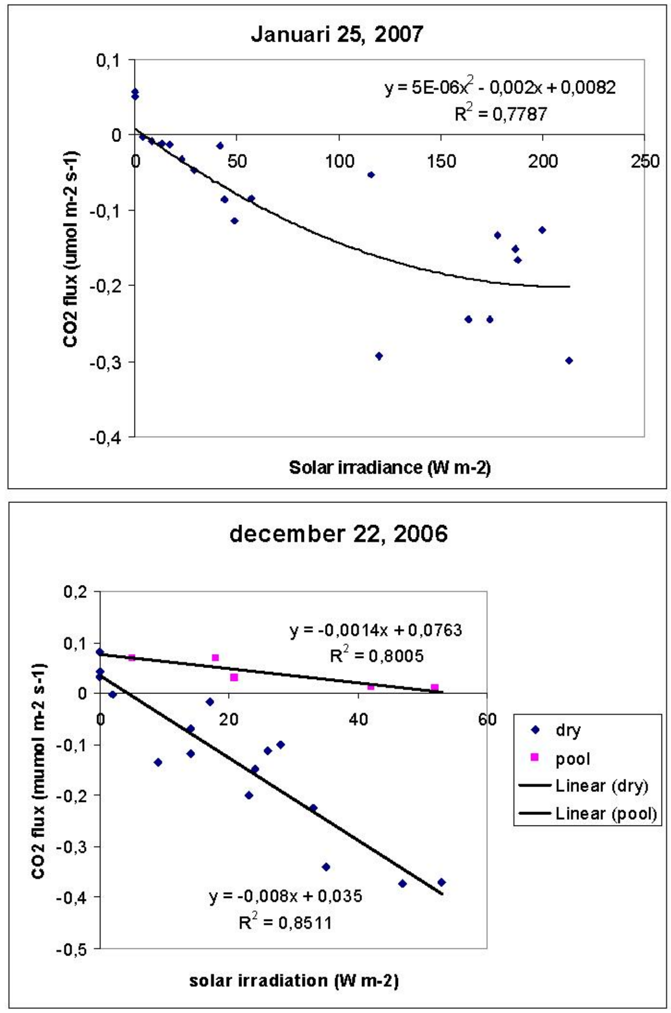

Fig. 7. CO_2 fluxes during wintertime on January 25, 2007 and December 22, 2006.

of the morning. Included are data when the soil was made dark. The result shows CO_2 release during dark conditions and uptake when sufficient light is available. Uptake of CO_2 during tends to dominate over respiration even during wintertime (fig. 7). Generally, differences between the fluxes of the four measurement locations are small but on December 22 fluxes from the site in the shallow pool were clearly deviating (fig. 7b). Note the small irradiance on this day when sun angle was low and the sky was cloudy.

C. *Open water measurements*

Figure 8 shows the partial pressure of CO_2: pCO_2 in the water of the Dollard estuary versus salinity of the water on May 23, 2006. At low salinity, so close to the river, pCO_2 is well above atmospheric CO_2 concentration, implying that CO_2 is released from the water to the atmosphere. At high salinity values, more representative for the Wadden Sea, pCO_2 decreases to values below atmospheric CO_2 concentration, implying that CO_2 is taken up by the water.

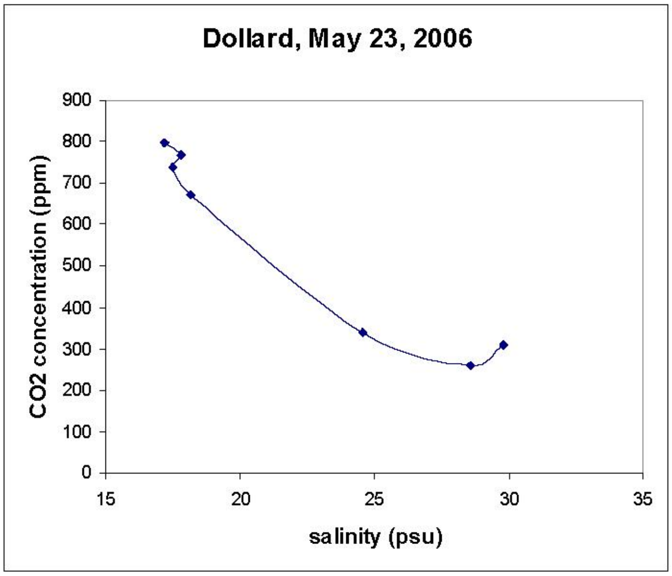

Fig. 8. Partial pressure of CO_2 in the water versus salinity in the Dollard estuary.

V. Discussion and Conclusion

The slow response ('acclimatization') of the CO_2 flux to changing irradiance on the tidal flat came as a surprise. The period of flux adaptation extends well over the period of acclimatization of algae. Slow acclimatization can be understood as algae live in a wet soil and CO_2 is not directly exchanged between algae and atmosphere, but instead indirectly via the water in the soil top layer. Slow acclimatization is advantageous for flux chamber measurements as it diminishes the influence of incomplete transparency of the flux chamber on the results. However, it complicates the relation between fluxes and irradiance. This problem was solved by relating CO_2 fluxes to mean irradiance during one hour before the start of the flux measurements.

Carbon dioxide fluxes during dark conditions were fitted exponentially to temperature as the rate of many biochemical reactions increases exponentially with temperature. The large scatter around the exponential fit shows that other parameters also influence respiration rate. Unfortunately, the small data set until now does not permit to determine experimentally which other parameters affect respiration rate.

High correlations between CO_2 flux and irradiance have been found. The empirical fits agree with theoretical expectations of respiration during dark conditions and uptake of CO_2 for growth when sufficient light is available. The observation of a high correlation between CO_2 flux and irradiance is probably new, as older measurements in the field, based on oxygen measurements, could not relate algal production to irradiance [5].

Maximum uptake (over 4 μmol CO_2 m^{-2} s^{-1}) was an order of magnitude larger than observed on sandy beach [6]. The difference is attributed to higher algal densities on tidal flats.

The measurements indicate that the tidal flat is a year-round sink for atmospheric CO_2. At first, this result came as a surprise as observations in the southern North Sea, surrounding the Wadden Sea, show the area to be almost in equilibrium on a yearly timescale with some uptake of CO_2 in spring and release during autumn and winter [3]. However, older measurements [5] show primary production on a tidal flat in Eemshaven exceeding respiration during all seasons of year. By contrast, respiration exceeded primary production on tidal flats deeper into the Dollard estuary [5]. As conditions on the tidal flat of the present study are more similar to the Eemshaven than to sites within the estuary, it is concluded that the present observation of a year-round uptake of CO_2 at the tidal flat agrees with previous measurements.

The shipborne measurement is in line with observations in the southern North Sea [3] and European estuaries [4]: CO_2 uptake in the Wadden Sea in spring and CO_2 release in the Dollard estuary.

Acknowledgment

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